SPECIFICATION FOR THE SOFIA VACUUM PUMPING SYSTEM

APP-AR-SPE-SE01-028

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SPECIFICATION FOR THE SOFIA VACUUM PUMPING SYSTEM

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(Science Project Approvals)

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REVISIONS

Revisions to the document from the previous issue are denoted by vertical bars in the margin of the page.

REV	DATE	DESCRIPTION	APPROVAL
A	9/1/2009	The current specification APP-AR-SPE-SE01-028 Rev.A replaces the unbaselined SE01-028 specification draft. The original SE01-028 specification included a vacuum-pumping system and blower system. The requirements have since been modified and the current specification includes the vacuum-pumping system only. The need for a blower system specification has yet to be determined. A new document number has also been assigned here according to new document identification format. Baselined	SPCB

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SPECIFICATION FOR THE SOFIA VACUUM PUMPING SYSTEM

1.0   SCOPE

1.1 Purpose

The purpose of this specification is to define the requirements for the Science Instrument (SI) Vacuum Pumping System of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Project. This system comprises one of four systems defined in the New Mission Subsystems Specification, SE01-011. The New Mission Subsystem specification calls for a flight qualified vacuum-pumping subsystem capable of supporting science instrument cryogenic dewars and telescope assembly instrument flange tub evacuation.

The presented specification replaces the unbaselined SE01-028 draft specification, "Item Development Specification for the SOFIA Vacuum Pumping and Blower System," which was submitted but not approved by the Government. The original SE01-028 specification from August 2000 defined requirements for the SOFIA SI Vacuum Pumping and Blower System. The system has since been changed to separate the vacuum pump and the blower. At the time of the writing of this document, no blower specification exists and the need of a blower system has yet to be determined. The presented specification APP-AR-SPE-SE01-028 consists only of the SOFIA vacuum pumping system.

1.2 Subsystem Description

A vacuum system is required for use by the mission operations team during flight. This vacuum system serves two purposes, to pump out the Nasmyth tub when needed and to support in-flight vacuum requirements of the Science Instruments.

Select science instrument systems use detectors that require temperatures lower than the liquid helium bath temperature of 4.2 K for optimum operation. In order to optimize detector response and noise level, it is necessary to pump on the liquid helium bath to lower the temperature between 1.5 K and 2 K. The type of pumping system required is a standard mechanical pump with sufficient pump speed and throughput such that a sufficiently low pressure can be achieved within a reasonable time. In addition, some instruments will require that their optical path be evacuated as part of onboard testing or as part of operations.

2.0   APPLICABLE DOCUMENTS

Configuration-controlled documents will be the latest revisions available, unless otherwise stated as specific revisions.

2.1 Required Documents

DCP-O-018, Environmental Acceptance Testing, Electronic and Electromechanical Testing

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PM06-001, Electromagnetic Interference and Compatibility Control Plan

SE01-011, New Mission Subsystems Specification

SE09-015, Parts, Materials, and Processes Program Plan

SOF-SPE-KT-4000.0.02, Flange Assembly Description

TA_AS_11, SE03-018, TA Assembly / Aircraft System Exhaust Tube and Vacuum Line (s) Interface

TA_SI_01, SE03-036, Cable Load Alleviator Device / Science Instrument Cable Interface

TA_SI_02, SE03-037, Telescope Assembly / Science Instrument Mounting Interface

USRA-DAL-1006-00, Corrosion Prevention Guidelines for the Development Phase of the SOFIA Project

USRA-DAL-1093-00, Environmental Requirements for the SOFIA Observatory (USRA)

USRA-DAL-1126-00, Structural Design Criteria for the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program

2.2 Guidance Documents

MIL-STD-1472D, Human Engineering Design Criteria [Feb. 1994/Rev. D, Notice 3]
NPR 6000.1, NASA Requirements for Packaging, Handling, and Transportation [March 2005/Rev. G]

PM23-001, SOFIA Integrated Logistics Support Plan

PD-2009, SOFIA Lexicon

SCI-AR-PLA-PM21-2000, Science Project System Safety and Mission Assurance Plan

3.0   REQUIREMENTS

3.1   Performance

3.1.1   The Vacuum Pumping System shall support a pumped liquid helium bath capable of dissipating 350 mW at 1.75 K.

Trace: SE01-011, section 3.1.13

Rationale: FIFI-LS requires less than 300 mW of power dissipation at 1.75 K. The vacuum pump requirement presented here will meet and exceed the

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requirement of FIFI-LS. A lower temperature can be achieved by reducing the thermal load if required. This should cover any reasonable instrument design down to the lower limit of this cooling technique.

3.1.1.1   The pressure of the helium bath shall be reduced to at least 10.126 torr when the vacuum system is operating at full pumping speed.

Trace: 3.1.1

Rationale: This is the bath pressure that corresponds to a temperature of 1.75 K.

3.1.1.2   The pumping speed at 10.126 torr shall be at least 550 liters/minute for each vacuum pump.

Trace: 3.1.1

Rationale: This is the pump speed needed to overcome the boil-off as the bath goes through the lambda point.

3.1.1.3   The pumping speed shall be controllable over the continuous range of zero to 550 liters/minute.

Trace: 3.1.1

Rationale: Pumping speed must be controlled while the bath temperature is reduced below 4.2 K otherwise excessive loss of cryogens will result in reduced instrument operation time.

3.1.2   The Vacuum Pumping System shall be able to evacuate a volume two times the volume of the Instrument Flange (INF) (INF volume = 201 liters) to 22.5 torr, with an additional leak load of 0.3 liters/second in 90 min.

Trace: SOF-SPE-KT-4000.0.02, section 5.2.2.2

Rationale: Some science instruments require an evacuated internal optical path as part of operations or onboard testing. The combined volume of the instrument and INF will be less than three time that of the INF interior. A leak rate has been incorporated into this requirement as the system will have both real and virtual (trapped volume) leaks.

3.2   Physical

3.2.1   The Vacuum Pumping System shall be connected from the pump to the CLA drape via 1.25 inch inner diameter or greater lines.

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Trace: TA_SI_01, Appendix

Rationale: Existing equipment on the platform.

3.2.2 The lines in the CLA drape shall be flexible, corrugated, steel jacketed tubing of 1.63 inch outer diameter and 1.25 inch inner diameter.

Trace: TA_SI_01, Appendix

Rationale: Existing equipment on the platform.

3.2.3 The Vacuum Pumping System controls (power switch and pumping speed controls) shall be accessible to the Mission Crew during flight and ground operations.

Trace: SE01-011, section 3.1.13

Rationale: Adjustments to the vacuum system will need to be done when an instrument is in operation (line-ops and flights) so the controls must be accessible.

3.2.4 Vacuum-line routing disconnect panel to the pump speed control system shall be in accordance with SE03-036 (TA_SI_01) Section 4 Interface Requirements.

Trace: TA_SI_01, section 4

Rationale: Existing equipment on the platform.

3.2.5 Vacuum lines shall be attached to the disconnect panel using KF40 (Quick Connect) fittings.

Trace: SE03-018 (TA_AS_11), section 3.1.1

Rationale: Existing equipment on the platform.

3.2.6 Vacuum lines shall be attached to the INF tub using standard KF25 (Quick Flanges) fittings including centering rings and clamps.

Trace: TA_SI_02, section 4.5.3

Rationale: Existing equipment on the platform.

3.2.7 The Vacuum Pumping System shall use less than 10 kVA.

Trace: None found.

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Rationale: This estimate incorporates worst-case information from the data sheets of commonly available vacuum pumps.

3.2.8 The Vacuum Pumping System shall weigh no more than 330 pounds.

Trace: None Found

Rationale: This estimate incorporates worst-case information from the data sheets of commonly available vacuum pumps.

3.2.9 The Vacuum Pumping System shall make the data from its digital pressure transducers available over MCCS housekeeping through connecter J54 (a D38999/F20FB35SN that mates with D38999/F20FB35PN) on the PI Patch Panel using RS232 serial connection.

Trace: MCCS_SI_02, section 3.2.5

Rationale: The SI instrument teams and platform will want to monitor pressure during certain SI instrument operations.

3.3 Functional

3.3.1 The Vacuum Pumping System shall use oil-free vacuum pumps.

Trace: None found.

Rationale: Oil from an oil vacuum pump can back-stream into a science instrument or the tub, contaminating sensitive components of the SI or TA. This requirement also eliminates the hazard of oil contamination in the aircraft cabin. Numerous oil-free vacuum pump options are available.

3.3.2 Each vacuum-pumping speed control system shall have one high-pressure gauge with a measurement range of 0 torr to 800 torr with a precision of 1.6 torr and an accuracy of 2.64 torr and a low-pressure gauge with a range of 0 torr to 100 torr with a precision of 0.2 torr and an accuracy of 0.33 torr.

Trace: SE01-011, section 3.1.13

Rationale: Vacuum gauging by the manifold is necessary for reference when adjusting the manifold and for diagnostic purposes.

3.3.3 Each vacuum pump shall have a digital pressure transducer with a measurement range of 1 to 1000 torr accurate to within 1% or better of the current reading and a precision of 0.3 torr located near the relevant point of pressure control (e.g. pumped helium bath, INF port). Note this data will be available to SI teams through MCCS housekeeping.

Trace: SE01-011, section 3.1.13

Rationale: Measurement of the pressure should be handled at the point that gives the information at the point that is being monitor or controlled. All relevant pressures are greater than 1 torr.

3.3.4   Each vacuum pump shall have a valve to isolate it from the rest of the pump system.

Trace: None found.

Rationale: It is desirable to isolate the vacuum pump from the system so that changes to the vacuum lines (e.g. rerouting, checking of seals) do not require shutting down the pump as temporary shut downs will minimize vacuum degradation.

3.3.5   Each pump shall have a valve that will allow it to be vented to cabin pressure while the pump is isolated from the rest of the pumping system.

Trace: None found.

Rationale: This will enable the pump to be worked on without venting the entire vacuum system.

3.3.6   Each vacuum line shall have a valve that will allow it to be vented to cabin pressure independent of the vacuum pump.

Trace: None found.

Rationale: This will enable work on the vacuum system without having to shut down the pump and vent the entire system.

3.3.7   There shall be a provision for using a vacuum valve to isolate the INF Interior at the KF25 flange from the vacuum line.

Trace: None found.

Rationale: The INF can be left with its interior evacuated when the vacuum pumps are powered down in support of instrument or platform operations.

3.3.8   The Vacuum Pumping System shall be able to perform at least two independent vacuum pumping operations at the same time (i.e. two pumps). Both with a pumping speed of at least 550 liters/minute for each vacuum pump.

Trace: SE01-011, section 3.1.13

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Rationale: It will be necessary at some point to pump on two cryogen baths at the same time or a cryogen bath and the INF.   This also supplies a ready back-up when only a single system is needed.

3.4   Environmental

3.4.1   The Vacuum Pumping System electrical equipment shall be designed for Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) in accordance with the Electromagnetic Interference and Compatibility Control Plan, PM06-001.

3.4.2   The Vacuum Pumping System equipment shall meet the steady state temperature requirements in accordance with USRA-DAL-1093-00, section 2.3.

3.4.3   The Vacuum Pumping System shall operate in the vibration environment in accordance with USRA-DAL-1093-00, section 2.2.

3.4.4   The Vacuum Pumping System equipment shall meet the altitude requirements in accordance with USRA-DAL-1093-00, section 2.4.

3.4.5   The Vacuum Pumping System shall meet the shock requirements in accordance with USRA-DAL-1093-00, section 2.4.

3.4.6   The Vacuum Pumping System equipment shall meet the humidity requirements in accordance with USRA-DAL-1093-00, section 2.4.

3.4.7   The Vacuum Pumping System component installation shall be designed to withstand the aircraft limit loads in accordance with USRA-DAL-1126-00, section 2.0.

3.4.8   The Vacuum Pumping System component installation shall be designed to withstand the aircraft ultimate loads in accordance with USRA-DAL-1126-00, section 2.0.

3.4.9   The Vacuum Pumping System component installation shall be designed to withstand the emergency landing loads in accordance with USRA-DAL-1126-00, section 2.0.

3.5   Safety

3.5.1   The Vacuum Pumping System shall meet the applicable SOFIA airworthiness requirements including DCP-O-018.

3.5.2 Thermal Hazards, which in normal operation, expose personnel to surface temperatures which could cause injury, shall be appropriately guarded or placarded. Surface temperatures induced by climatic environment are exempt from this requirement.

3.5.3 The Vacuum Pumping System electrical equipment shall be capable of being shut down and locked-out for maintenance activities.

3.5.4 The Vacuum Pumping System power circuits shall include neutral safety ground and automatic voltage and current limiting devices in accordance with SCI-AR-PLA-PM21-2000.

3.5.5 Energized electrical connections shall be protected against contact with personnel in accordance with SCI-AR-PLA-PM21-2000.

3.6 Reliability

3.6.1 The Vacuum Pumping System will use a reliable vacuum pump suitable for handling vapors and gasses and at least 12 hours of continual operation.

3.7 Maintainability

3.7.1 The vacuum pump shall be mounted such that it can be swapped with a replacement pump within 3 hours or less.

3.7.2 Each vacuum pump shall be capable of operating at least 10,000 hours before it needs a major service.

3.7.3 There shall be a spare vacuum pump available for replacement.

3.7.4 There shall be parts and materials for servicing a vacuum pump in stock.

3.8 Logistics

3.8.1 The Vacuum Pumping System shall use standard tools for maintenance and inspections in accordance with PM23-001.

3.9 Parts, Materials and Processes

3.9.1 The Vacuum Pumping System design shall select parts, materials, and processes from commercial aircraft industry practices.

3.9.2 The Vacuum Pumping System design shall include a protective plating or coating to all metal surfaces which are not corrosion resistant, except where electrical grounding is required, in accordance with USRA-DAL-1006-00.

3.9.3 The Vacuum Pumping System design shall not use materials which through out-gassing cause the deterioration of other materials or the degradation of performance of onboard equipment in accordance with the Parts, Materials and Processes Program Plan, SE09-015.

4.0 VERIFICATION OF REQUIREMENTS

4.1 Methods of Verification

4.1.1 Analysis: An element of verification that utilizes established technical or mathematical models or simulations, algorithms, charts, graphs, circuit diagrams, or other scientific principles and procedures to provide evidence that stated requirements were met.

4.1.2 Demonstration: An element of verification which generally denotes the actual operation, adjustment, or re-configuration of items to provide evidence that the designed functions were accomplished under specific scenarios. The items may be instrumented and quantitative limits of performance may be monitored.

4.1.3 Inspection: An element of verification consisting of investigation, without the use of special laboratory appliances or procedures, or items to determine conformance to those specified requirements, which can be determined, by such investigations. Examination is generally non-destructive and typically includes the use of sight, hearing, smell, touch, and taste; simple physical manipulation; mechanical and electrical gauging and measurement; and other forms of investigation.

4.1.4 Test: An element of verification, which generally denotes the determination, by technical means, of the properties or elements of items, including functional operation, and involves the application of established scientific principles and procedures.

4.2 Requirements Specification

Paragraph ID	Type	Vacuum Pump System Capability	Verification Method
3.1.1	Performance	The Vacuum Pumping System shall support a pumped liquid helium bath capable of dissipating 350 mW at 1.75 K.	Analysis Test
3.1.1.1	Performance	The pressure of the helium bath shall be reduced to at least 10.126 torr when the vacuum system is operating at full pumping speed.	Analysis Demonstration
3.1.1.2	Performance	The pumping speed at 10.126 torr shall be at least 550 liters/minute for each vacuum pump.	Analysis Demonstration
3.1.1.3	Performance	The pumping speed shall be controllable over the continuous range of zero to 550 liters/minute.	Analysis Demonstration
3.1.2	Performance	The Vacuum Pumping System shall be able to evacuate a volume two times the volume of the Instrument Flange (INF) (INF volume = 201 liters) to 22.5 torr, with an additional leak load of 0.3 liters/second in 90 min.	Analysis Test
3.2.1	Physical	The Vacuum Pumping System shall be connected from the pump to the CLA drape via 1.25 inch inner diameter or greater lines.	Inspection
3.2.2	Physical	The lines in the CLA drape shall be flexible, corrugated, steel jacketed tubing of 1.63 inch outer diameter and 1.25 inch inner diameter.	Inspection
3.2.3	Physical	The Vacuum Pumping System controls (power switch and pumping speed controls) shall be accessible to the Mission Crew during flight and ground operations.	Inspection
3.2.4	Physical	Vacuum-line routing disconnect panel to the pump speed control system shall be in accordance with SE03-036 (TA_SI_01) Section 4 Interface Requirements.	Inspection
3.2.5	Physical	Vacuum lines shall be attached to the disconnect panel using KF40 (Quick Connect) fittings.	Inspection
3.2.6	Physical	Vacuum lines shall be attached to the INF tub using standard KF25 (Quick Flanges) fittings including centering rings and clamps.	Inspection
3.2.7	Physical	The Vacuum Pumping System shall use less than 10 kVA.	Inspection
3.2.8	Physical	The Vacuum Pumping System shall weigh no more than 330 pounds.	Inspection
3.2.9	Physical	The Vacuum Pumping System shall make the data from its digital pressure transducers available over MCCS housekeeping through connecter J54 (a D38999/F20FB35SN that mates with D38999/F20FB35PN) on the PI Patch Panel using RS232 serial connection.	Inspection
3.3.1	Functional	The Vacuum Pumping System shall use oil-free vacuum pumps.	Inspection

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3.3.2	Functional	Each vacuum-pumping speed control system shall have one high-pressure gauge with a measurement range of 0 torr to 800 torr with a precision of 1.6 torr and an accuracy of 2.64 torr and a low-pressure gauge with a range of 0 torr to 100 torr with a precision of 0.2 torr and an accuracy of 0.33 torr.	Inspection
3.3.3	Functional	Each vacuum pump shall have a digital pressure transducer with a measurement range of 1 to 1000 torr accurate to within 1% or better of the current reading and a precision of 0.3 torr located near the relevant point of pressure control (e.g. pumped helium bath, INF port). Note this data will be available to SI teams through MCCS housekeeping.	Inspection
3.3.4	Functional	Each vacuum pump shall have a valve to isolate it from the rest of the pump system.	Inspection
3.3.5	Functional	Each pump shall have a valve that will allow it to be vented to cabin pressure while the pump is isolated from the rest of the pumping system.	Inspection
3.3.6	Functional	Each vacuum line shall have a valve that will allow it to be vented to cabin pressure independent of the vacuum pump.	Inspection
3.3.7	Functional	There shall be a provision for using a vacuum valve to isolate the INF Interior at the KF25 flange from the vacuum line.	Inspection
3.3.8	Functional	The Vacuum Pumping System shall be able to perform at least two independent vacuum pumping operations at the same time (i.e. two pumps). Both with a pumping speed of at least 550 liters/minute for each vacuum pump.	Demonstration
3.4.1	Environmental	The Vacuum Pumping System electrical equipment shall be designed for Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) in accordance with the Electromagnetic Interference and Compatibility Control Plan, PM06-001.	Inspection
3.4.2	Environmental	The Vacuum Pumping System equipment shall meet the steady state temperature requirements in accordance with USRA-DAL-1093-00, section 2.3.	Inspection
3.4.3	Environmental	The Vacuum Pumping System shall operate in the vibration environment in accordance with USRA-DAL-1093-00, section 2.2.	Inspection
3.4.4	Environmental	The Vacuum Pumping System equipment shall meet the altitude requirements in accordance with USRA-DAL-1093-00, section 2.4.	Inspection
3.4.5	Environmental	The Vacuum Pumping System shall meet the shock requirements in accordance with USRA-DAL-1093-00, section 2.4.	Inspection
3.4.6	Environmental	The Vacuum Pumping System equipment shall meet the humidity requirements in accordance with USRA-DAL-1093-00, section 2.4.	Inspection
3.4.7	Environmental	The Vacuum Pumping System component installation shall be designed to withstand the aircraft limit loads in accordance with USRA-DAL-1126-00, section 2.0.	Analysis

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3.4.8	Environmental	The Vacuum Pumping System component installation shall be designed to withstand the aircraft ultimate loads in accordance with USRA-DAL-1126-00, section 2.0.	Analysis
3.4.9	Environmental	The Vacuum Pumping System component installation shall be designed to withstand the emergency landing loads in accordance with USRA-DAL-1126-00, section 2.0.	Analysis
3.5.1	Safety	The Vacuum Pumping System shall meet the applicable SOFIA airworthiness requirements including DCP-O-018.	Analysis Inspection
3.5.2	Safety	Thermal Hazards, which in normal operation, expose personnel to surface temperatures which could cause injury, shall be appropriately guarded or placarded. Surface temperatures induced by climatic environment are exempt from this requirement.	Inspection
3.5.3	Safety	The Vacuum Pumping System electrical equipment shall be capable of being shut down and locked-out for maintenance activities.	Inspection
3.5.4	Safety	The Vacuum Pumping System power circuits shall include neutral safety ground and automatic voltage and current limiting devices in accordance with SCI-AR-PLA-PM21-2000.	Inspection
3.5.5	Safety	Energized electrical connections shall be protected against contact with personnel in accordance with SCI-AR-PLA-PM21-2000.	Inspection
3.7.1	Maintainability	The vacuum pump shall be mounted such that it can be swapped with a replacement pump within 3 hours or less.	Analysis Demonstration
3.7.2	Maintainability	Each vacuum pump shall be capable of operating at least 10,000 hours before it needs a major service.	Inspection
3.7.3	Maintainability	There shall be a spare vacuum pump available for replacement.	Inspection
3.7.4	Maintainability	There shall be parts and materials for servicing a vacuum pump in stock.	Inspection
3.8.1	Logistics	The Vacuum Pumping System shall use standard tools for maintenance and inspections in accordance with PM23-001.	Inspection
3.9.1	Parts, Materials, and Processes	The Vacuum Pumping System design shall select parts, materials, and processes from commercial aircraft industry practices.	Inspection
3.9.2	Parts, Materials, and Processes	The Vacuum Pumping System design shall include a protective plating or coating to all metal surfaces which are not corrosion resistant, except where electrical grounding is required, in accordance with USRA-DAL-1006-00.	Inspection
3.9.3	Parts, Materials, and Processes	The Vacuum Pumping System design shall not use materials which through out-gassing cause the deterioration of other materials or the degradation of performance of onboard equipment in accordance with the Parts, Materials and Processes Program Plan, SE09-015.	Inspection

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5.0   ACRONYMS

CLA   Cable Load Alleviator
INF   Instrument Flange
SI   Science Instrument

6.0   NOTES

NA

7.0   APPENDIX

7.1   Pumped Helium Bath Cryostat and its Vacuum Requirements

The following is a discussion of what must be considered when using a pumped liquid helium bath cryostat. In particular the vacuum pumping requirements for reducing the vapor pressure in the bath will be examined. Initial assumptions are that we are reducing the bath pressure slowly so additional thermodynamic effects will not increase the cryogen consumption.

The principle of what we want to accomplish is simple; reduce the pressure on the liquid bath that is cooling your experiment and you reduce the boiling point and so the temperature of the bath. This cooling is accomplished by the energy in the phase change between liquid and gaseous cryogen, which is called the latent heat (L).   In this case the cryogen is liquid helium

Liquid helium has a variety of unusual properties having to do with its second liquid state, the supper fluid state, called the He II state. Two of these are of concern when pumping on a liquid helium bath: the lambda (λ) point and the frictionless flow of He II.

The lambda point is the sudden increase in the specific heat (C_s) of liquid helium that marks the phase change between normal helium (He I) and super fluid helium (He II). What this mean to the cooling process is that much more energy must be removed for each mole of the bath to reduce its temperature. Figure 1 shows the temperature dependence of the specific heat of liquid helium between 4.1K and 1K.

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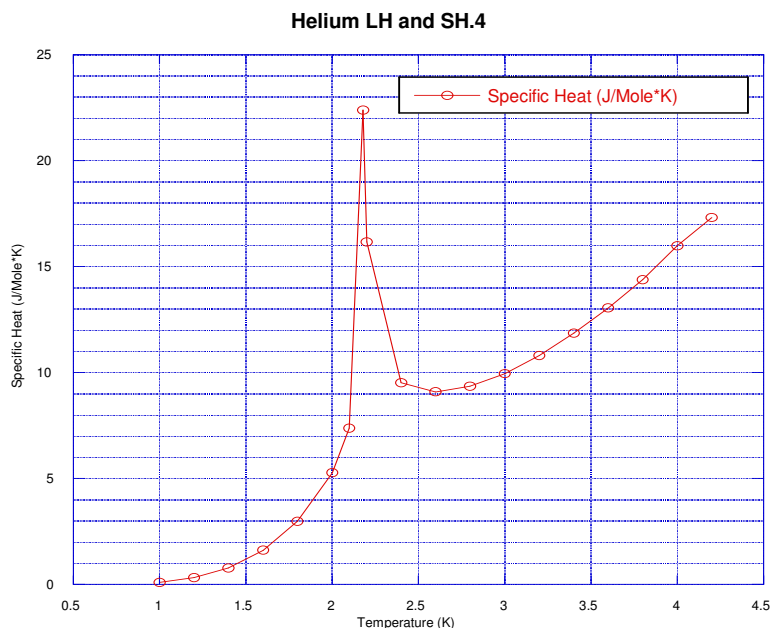
Helium LH and SH.4

Figure 1. Specific Heat of Liquid Helium vs. Temperature

What this means to the vacuum pumping process is that much more helium is changing from liquid to gas for each mille-Kelvin we reduce the bath temperature so we must remover more volume of gas to cool the bath.

Given the heat capacity C_s and the latent heat L we can calculate approximately how much gas will need to be removed from the system per each liter of liquid helium.

A table of the latent heat and molar volumes can be found on page 112 of <u>Helium-3 and Helium-4</u> by Keller with a table for the specific heat in The <u>Physicist Desk Reference</u> by Russell J. Donnelly being on page 119. The specific heal is in J/mole*K and latent heat is in J/mole.

Calculation of the amount of energy needed to be removed from the system for each mole of liquid helium to reduce it a temperature $\Delta T = T_1 - T_2$ is given simply by

$$\Delta E = \Delta t C_s$$

With the units of ΔE being in J/mole. A preferred form of this for this calculation would be J/L. The Molar Volume V_m is given in cm^3/mole and since there are 1000 cm^3 in a liter we can convert this to the Molar Volume in L/mole. Dividing by the molar volume in L/mole gives ΔE in J/L.

The question is how much helium needs to be boiled off for this change in energy? The latent heat L is given in J/mole we want that in J/L so we use the same Molar Volume as in the ΔE unit conversion to change L to J/L.

Now assume a 1 liter initial bath volume. Multiply ΔE by that volume to get the change energy for a 1 liter system. Then divide by the latent heat L in J/L for the change in volume.

Now keep in mind that as the bath cools the volume changes so the amount of liquid that needs to be cooled will also change. To handle this the calculation has been handled in steps that match the table cited earlier with volume for current step being take from the end result of

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the previous step (first step is a volume of one liter). So the last column of the table is the total boil-off of liquid helium.

The astute reader will ask what about cooling the rest of the mass of the system? The specific heat of the liquid helium is so much higher that that most other materials at this temperature that other mass can be ignored for this calculation. For example the specific heat of copper is less than 1 mJ/mole*K at 1 Kelvin.

Temp. (K)	ΔT (K)	L (J/mole)	Cs J/mole*K	ΔE (J/mole)	Vm (cubic-cm/mole)	Vm (liter/mole)	ΔE (J/liter)	L (J/liter)	Bath Vol (L)	Boil-Off (L)
1	0.2	80.22	0.101	0.0202	27.59	0.02759	0.73215	2907.6	0.7107	0.2893
1.2	0.2	84.17	0.322	0.0644	27.59	0.02759	2.3342	3050.7	0.7112	0.2888
1.4	0.2	87.76	0.78	0.156	27.48	0.02748	5.6769	3193.6	0.7125	0.2875
1.6	0.2	90.74	1.62	0.324	27.57	0.02757	11.752	3291.3	0.715	0.285
1.8	0.2	92.72	2.98	0.596	27.53	0.02753	21.649	3368	0.7197	0.2803
2	0.1	93.13	5.27	0.527	27.48	0.02748	19.178	3389	0.7238	0.2762
2.1	0.08	93.13	7.38	0.5904	27.48	0.02748	21.485	3389	0.7284	0.2716
2.18	0.02	90.75	22.389	0.44778	27.39	0.02739	16.348	3313.3	0.732	0.268
2.2	0.2	90.75	16.166	3.2332	27.39	0.02739	118.04	3313.3	0.759	0.241
2.4	0.2	91.73	9.53	1.906	27.53	0.02753	69.234	3332	0.7751	0.2249
2.6	0.2	92.8	9.088	1.8176	27.73	0.02773	65.546	3346.6	0.7906	0.2094
2.8	0.2	93.58	9.358	1.8716	28	0.028	66.843	3342.1	0.8068	0.1932
3	0.2	93.91	9.951	1.9902	28.32	0.02832	70.275	3316	0.8242	0.1758
3.2	0.2	93.75	10.807	2.1614	28.73	0.02873	75.231	3263.1	0.8437	0.1563
3.4	0.2	92.99	11.859	2.3718	29.21	0.02921	81.198	3183.5	0.8658	0.1342
3.6	0.2	91.64	13.048	2.6096	29.77	0.02977	87.659	3078.3	0.8911	0.1089
3.8	0.2	89.53	14.385	2.877	30.41	0.03041	94.607	2944.1	0.9225	0.0775
4	0.2	86.56	15.991	3.1982	31.14	0.03114	102.7	2779.7	0.9579	0.0421
4.2	0.2	82.34	17.323	3.4646	31.97	0.03197	108.37	2575.5	1	0

Table 1. Pump-down Calculations

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If we graph out the boil-off rate as the bath cools the following is seen. There is a significant jump in the amount of helium consumed that corresponds to going though the lambda point. The total change between 2.2 and 2.18K is 0.027042 liters of liquid (see the highlighted numbers).
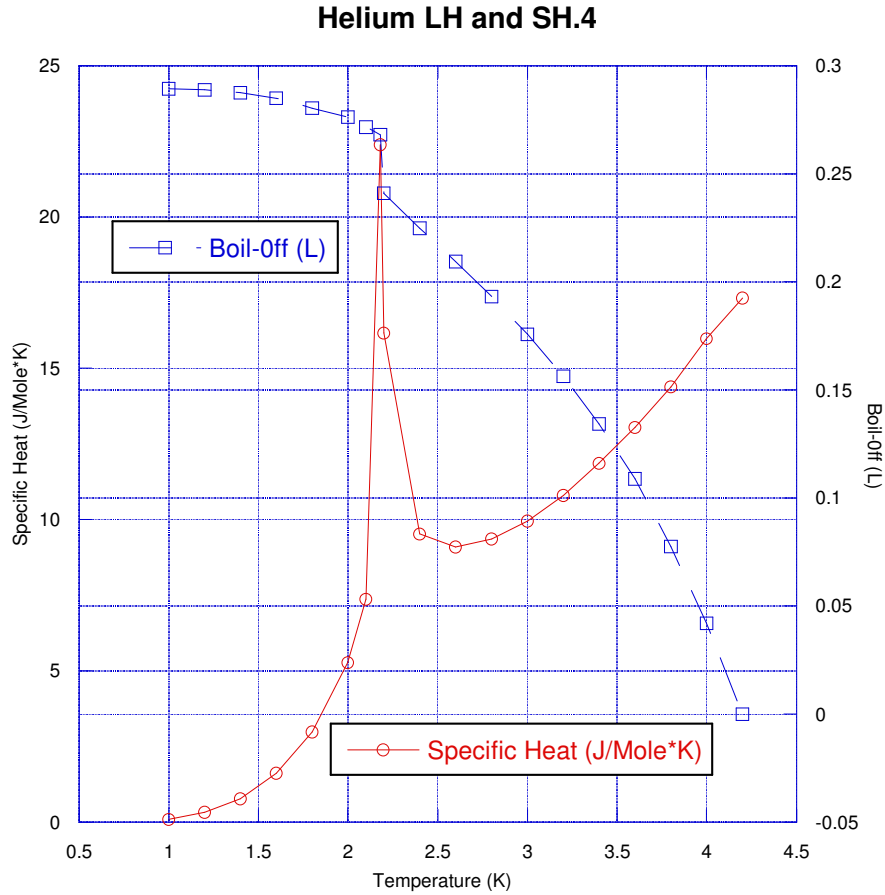
Helium LH and SH.4

Figure 2. Boil-Off of Liquid Helium

Now convert that to mole by dividing by the Molar Volume to get approximately 1 mole of boil-off. Use the ideal gas law to calculate the volume at the pressure corresponding (temperature is 297K pressure is in Pascal so convert from Torr).

$$PV = nRT \Rightarrow V = \frac{nRT}{P}$$

This gives a value in cubic meter, so multiply by 1000 to convert to liters.

$$V = 1000\left(\frac{nRT}{P}\right)$$

Taking the values form the other earlier table and plugging into this equation gives the following.

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Temp (K)	Volume Change (L)	Pressure (Torr)	Volume of helium at Pressure (L)
1	0.019724	0.12	3044.3
1.2	0.045904	0.625	1360.3
1.4	0.09291	2.155	798.51
1.6	0.16779	5.69	546.16
1.8	0.14877	12.466	221.03
2	0.16803	23.767	130.94
2.1	0.13143	31.428	77.456
2.18	0.98731	38.55	474.34
2.2	0.58803	40.465	269.14
2.4	0.56249	63.304	164.57
2.6	0.58186	93.733	114.97
2.8	0.62384	132.95	86.904
3	0.68682	182.07	69.866
3.2	0.7686	242.27	58.759
3.4	0.86876	314.7	51.129
3.6	1.0547	400.47	48.778
3.8	1.1639	500.69	43.053
4	1.3512	616.54	40.591

Table 2. Conversion to Gas Volume at Pressure

Referencing the value at 2.18 Kelvin we will need to remove 474.34 Liters of helium at 38.55 Torr to cool past the lambda point for every liter of initial bath volume. That leaves two remaining question: How much initial bath volume do we need and how fast do we need to remove this volume.

Now the amount of cryogen needed at 1.75 K needs to be calculated.

FIFI-LS during early test needed to dissipate 465 mW of power. They plan to have their thermal load down to less than 300 mW. The power dissipation budget should exceed that by a fair amount so let set it at 350 mW. If a larger power budget is used then the bath size starts to get prohibitively large (500 mW would require a bath of approximately 17 liter).

The first step is to determine the bath pressure required to have the bath temperature be reduced to 1.75K. To do this the international temperature scale for helium 4 was used. This gives a bath pressure of 10.126 Torr (13.49 mbar).

Next we need the latent heat of helium at 1.75K. From Keller Helium-3 and Helium-4 the latent heat at 1.6 K is 90.74 J/mole and at 1.8 K it is 92.72 J/mole. Interpolating between these points gives the latent heat at 1.75K as 92.225 J/mole.

350 mW the amount of helium that will be boiled off is as follows.
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$$Power = 350mW = 0.350W = 0.350 \frac{J}{s}$$

So

$$Boil - OFF = \frac{0.350\,J/s}{92.225\,J/mole} = 7.048x10^{-3}\,moles/s$$

So the pump speed must be such that it will remove $7.048x10^{-3}\,moles/s$ at 10.126 Torr. What does this mean in pump speed? Pump speed is generally given in volume per time so this needs to be converted into the volume needed to contain the needed amount of gas at the desired pressure.

Using the ideal gas law to calculate the volume of the gas boiled off
$$V = \frac{nRT}{P}$$

$P = 10.126Torr = 1350Pa = 1350\,N/m^2$
n= number of moles
R= 8.314 J/K*mole
T=297K

So the Volume V is as follows
$$V = \frac{nRT}{P} = \frac{(4.048x10^{-3}\,moles)(8.314\,\frac{J}{K \cdot mole})(297K)}{1350Pa} = 7.404x10^{-3}\,m^3$$

Multiply by 1000 to convert to liters and get 7.404 L/sec of gas boil-off.

There is an additional source of gas evaporation and that is the supper fluid film that will creep up the inside of the cryogen reservoir. The basis of this calculation was taken from <u>Mater and Methods at Low Temperatures</u> by Frank Pobell (the section on Supper Film Flow pages 25-27). Since supper fluid helium flows with zero friction it will for all effective purposed try and crawl out of the cryogen reservoir. When the film flows far enough up the neck of the reservoir that it hits the heat flow coming down it will then boil off. The question becomes what is the rate that the supper film is flowing up the neck. The following assumptions are made for this calculation: that the neck is fairly clean and well polished, the height above the surface of the bath to the evaporation point is about 5 cm.

Pobell writes that the thickness of the film d is (in nano-meters)

$$d = 30\left(h^{-1/3}\right)$$ where h is the height above the bath surface.

So

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$$d = 30\left(h^{-\frac{1}{3}}\right) = 30\left(5^{-\frac{1}{3}}\right) = 17.5nm$$

The typical film velocity v_f is 30 cm/s.

The circumference is $2\pi R$ (R=0.5 cm) so every second an area A moves up the neck.

$$A = 2\pi R v_f = 2\pi(0.5cm)(30cm) = 94.25cm^2$$

The thickness of the film d is 17.5 nm = 1.75×10^{-6} cm so the approximate volume, since this is a thin film, is Axd=1.65×10^{-4} cm^3. That is the volume every second so every minute 60 times that is evaporated or 9.9×10^{-3} cm^3.

The molar volume is 45.34 cm^3/mole so dividing by it gives

$$n = \frac{\left(9.9 x 10^{-3} cm^3\right)}{45.34 \, cm^3\!\Big/\!mole} = 2.19 x 10^{-4} \, mole$$

Now us the ideal gas law again so

$$V = \frac{nRT}{P} = \frac{\left(2.19 x 10^{-4} moles\right)\left(8.314 \, J\!\Big/\!K \cdot mole\right)\left(297K\right)}{1350 Pa} = 4 x 10^{-4} m^3 = 0.4L$$

So the is 0.4 L/min = 6.67×10^{-3} L/sec.

Add this to the heat dissipation boil-off and get the total boil-off rate of 7.41 L/s of helium gas.

Now given this boil-off rate of boil-off how big of a bath would we need to last 10 hours?

We are boiling off $7.048 x 10^{-3} \, moles/s + 2.19 x 10^{-4} \, moles/s = 7.267 x 10^{-3} \, moles/s$ of liquid helium at 1.75K so in 10 hours (36000 seconds) we will boil-off 261.6 moles the molar volume at 1.75 K is approximately 27.53 cubic cm per mole so multiplying gives 7202.2 cubic cm= 7.2 liters of liquid helium.

The rule of thumb for pumped helium baths that you total initial bath volume should be twice what you will use to stay cool at the final temperature. This takes into account cooling the helium in the bath and cooling the mass of the system.

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Consider a bath of 14.4 liters. We will use about 24% of that just cooling to 2.2K (see Table 1) so we will have 10.94 liters when we go through the lambda point. It will take pumping out approximately 5189 liter of gaseous helium ($V = 474.34 \times 10.94 = 5046.98L$) to cool through the lambda point. Given a limit of 10 minutes it would take a pump speed of 518.9 L/min or approximately 519 L/min.

7.2   Vacuum System Considerations

The equation for pumping speed S of a vacuum system with vacuum conductance C_l and vacuum pump speed S_p is as follows

$$\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C_l}$$

Now solving for the pumping speed gives

$$\frac{1}{S_p} = \frac{1}{S} - \frac{1}{C_l} \Rightarrow S_p = \frac{1}{\frac{1}{S} - \frac{1}{C_l}} = \frac{SC_l}{SC_l} \frac{1}{\frac{1}{S} - \frac{1}{C_l}} = \frac{SC_l}{\frac{SC_l}{S} - \frac{SC_l}{C_l}} = \frac{SC_l}{C_l - S}$$

Using VacTran to calculate the conductance vs. pressure of the CLA vacuum lines using a length of 1200cm (10m from the CLA lines plus 2m from the lines from the Counter Weight plate to pumping location) and an inner diameter of 3.175cm leads to the following figure. Conductance values have been corrected for the gas being pumped.

At 35 Torr the vacuum line conductance for helium is 195 L/s where as for air it is about 100 L/s. Plug this into the formula above for the needed pump speed and we get

$$S_p = \frac{SC_l}{C_l - S} = \frac{\left(519 \frac{L}{\min}\right)\left(11700 \frac{L}{\min}\right)}{\left(11700 \frac{L}{\min}\right) - \left(519 \frac{L}{\min}\right)} = 543 \frac{L}{\min}$$

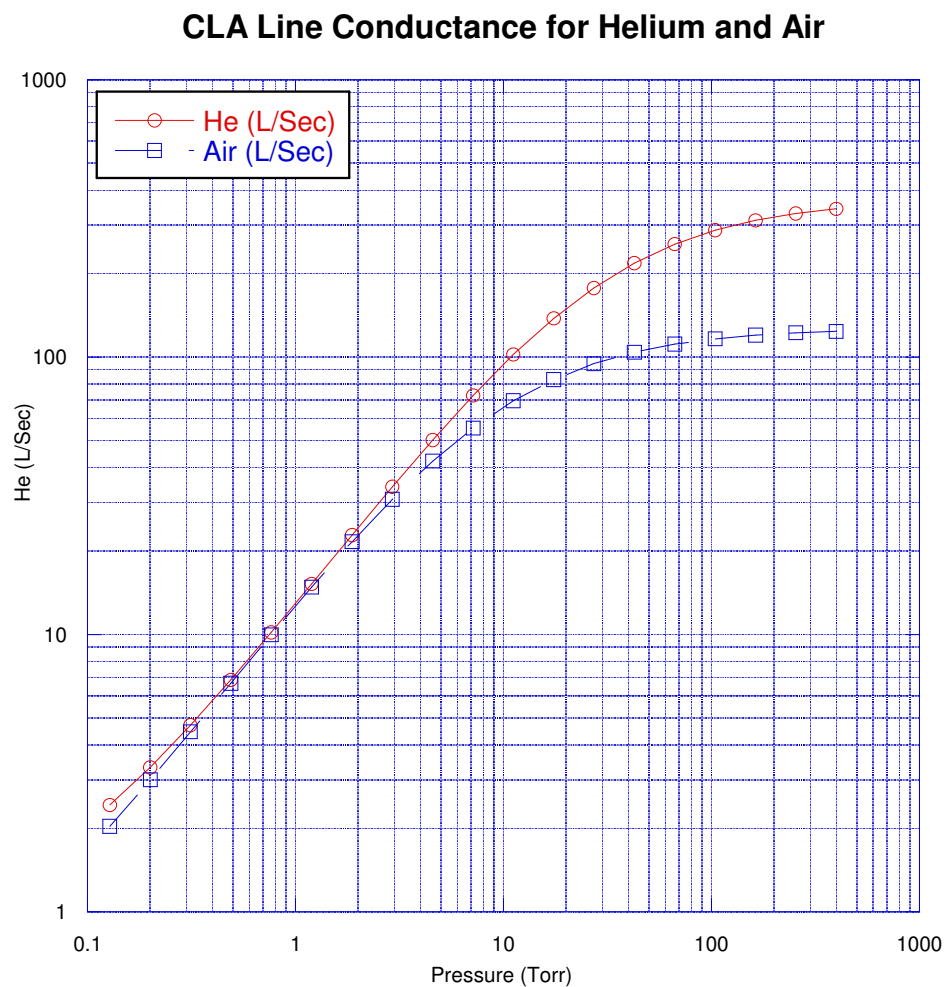## CLA Line Conductance for Helium and Air

Figure 3. CLA Line Conductance for Helium and Air

VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE